APPLICATION NOTE

41

DELCO RADIO

SEMICONDUCTORS

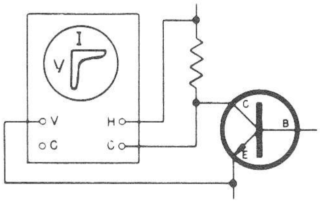
CURRENT MEASUREMENT FOR POWER TRANSISTOR LOAD LINE ANALYSIS

I. USE OF CURRENT MEASURING IN LOAD LINE ANALYSIS

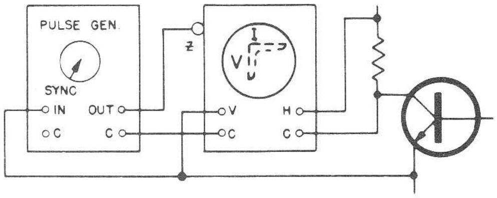
The Applications Engineering Group at Delco Radio has found load line analysis to be an important tool in the design and measurement of all types of power semiconductor circuitry. Despite the value of the technique, some engineers are reluctant to use it because of problems related to accurate display of current. This note describes the x-y oscilloscope presentation and discusses various techniques for current measurement as a part of the load line display.

Figure A shows a connection for displaying V_{CE} vs. I_C. This display is the most widely used and provides the most important information concerning the operation of the transistor. Here we see the maximum voltage, collector current, and dissipation experienced by the transistor. If we make one addition, Figure B, we have a quantitative display. By adding a pulse or square-wave generator, intensity timing markers are apparent in the display. The generator is synchronized to the basic frequency of the transistor circuit and then is increased to 10 or 20 times the basic frequency. The generator is connected to the Z or intensity axis of the oscilloscope to provide time measurement of peak conditions in the load line. Peak power and peak energy can be observed and compared to operating curves on data sheets. Normal, transient, and fault conditions can be observed and photographed.

TRANSISTOR LOAD LINE PORTRAYAL



V_{CE} vs. I_C Transistor Power Lissajous Figure.
FIGURE 1



V_{CE} vs. I_C Transistor Power Lissajous with Timing Markers Added to the "Z" Axis.
FIGURE B

Voltage measurement is usually not a problem with high input impedance oscilloscopes and compensated probes. Accurate current measurement, however, is more difficult because it usually involves breaking the circuit and inserting additional impedance. This report describes current measuring techniques and describes experiments for evaluating these techniques.

II. TYPES OF CURRENT MEASUREMENT

There are four basic methods of current viewing: meters, current transformers, Hall effect devices, and resistors. Of interest here are the latter three methods because they make possible the display of current on an oscilloscope.

DELCO RADIO DIVISION
GENERAL MOTORS CORPORATION
KOKOMO, INDIANA
JANUARY 1969

A sampling resistor must be inserted in the circuit where current measurement is desired. The voltage drop across the resistor will be proportional to the current through it. Five types of resistors may be used to sample current: carbon, inductive wire wound, noninductive wire wound, straight resistance wire, tubular-shunt, or more descriptive; coaxial. The construction of two coaxial resistors is shown in Figures XVI and XVII (see appendix). The value chosen for the resistor depends on the amplitude of the current, the power capability of the resistor, the impedance presented to the circuit, and the sensitivity of the scope being used. Typical values may range from several thousandths of an ohm to several ohms.

The current probe or transformer is a very convenient way to measure current. Unlike the resistor method, the circuit does not have to be broken with the current probe. It simply clips around the wire, and forms a single turn of the primary of a transformer. A proportional voltage is measured at the secondary of the transformer.

Like the standard current probe, the Hall effect probe clips around the wire conducting the current to be measured. The probe assumes its name from the fact that it measures current using the Hall effect. The Hall effect is the interaction between an electric current and a magnetic field at right angles in a conductor or semiconductor, to produce a voltage in a direction perpendicular to the other two. The wire carrying the current is passed through a magnetic core and sets up a magnetic field proportional to the current. If the Hall effect device is placed in the magnetic field of the core and a current passed through the device, the Hall voltage will be proportional to the current in the wire.

III. PROBLEMS AND ANALYSIS

Measuring the collector current of a transistor for load line analysis can be difficult to accomplish accurately when fast switching times are concerned (less than 3μs). The cause of the problem can be generally attributed to the method in which the current is measured. Not only does the type of element (resistor, current transformer, etc.) used affect the reading of current, but also the connections between the element and the scope.

The five types of viewing resistors discussed in the previous section were used to sample a square wave in a circuit. The square wave is presented at 4 kHz and the fall time is 1.6μs in Figure I (photographs are shown in the appendix). Figures I through V show how the five resistors displayed the fall time of the square wave. As can be seen, the coaxial resistor is the best type of resistor for current sampling and the straight resistance wire is the worst. The difference between the noninductive wire-wound resistor and the wire-wound resistor seems to be small. To further show the validity of the fall time results, the same resistors were used to measure collector current to display the load line of the output transistor in a simulated television horizontal deflection circuit without the damper diode. The same results are shown in Figures X through XV. It may appear that the carbon resistor gives results comparable to the coaxial resistor. However, Figures VII and VIII illustrate the fact that for very fast switching times, the carbon resistor may present misleading results.

The self-inductance of a resistor plays an important role in the type of waveform displayed. A very low Q (X_L/R) is desirable and therefore dictates a small self-inductance and as large a resistance as possible. Each of the resistors in this experiment has a self-inductance in the range from 10 to 60 nanohenries. It can be seen that at frequencies above a megahertz, the inductance of the resistor can present a considerable impedance to the circuit. Although this may not affect the circuit appreciably, the induced voltage across the resistor may appear as an erroneous reading on the scope. The coaxial resistor has the smallest self-inductance; however, the major reason it gives the best results is the fact that the sensing pickup wire returns to the BNC connector through the center of the resistor (shown in Fig. XVI).

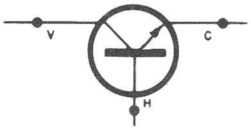
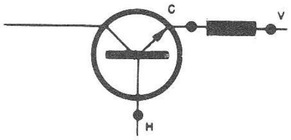
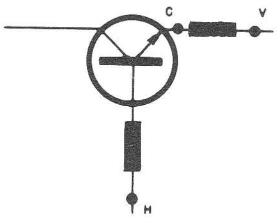
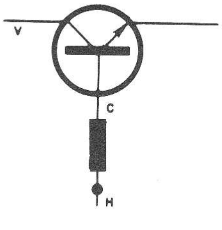
Figure XI illustrates how a current probe compares with the resistors and that, in certain cases, may be used for load line analysis with reliable results. The current probe gives very good results in the sine-wave frequency range of 1 kHz to 20 MHz. Care should be taken in measuring a square wave with a frequency below 25 kHz. The core material used in the probe will not sustain a constant flux, caused by a constant current value, for over 20μs without causing errors in the reading. A disadvantage is that the low-frequency response of the current probe is limited. The Hall effect probe overcomes this disadvantage because it has an extended frequency response, including dc. The exact specification for each type of probe can be obtained from the manufacturer.

As stated earlier, the connections between the element and the scope may contribute to the erroneous readings often encountered in viewing current. Clip leads are a major source of trouble. Many times, clip leads terminating a coaxial line are attached to the resistor. This changes the characteristic impedance of the coaxial line and may cause serious reflections. Also, stray pickup is increased with clip leads. All resistors used in this experiment have one-inch leads and were connected to the coaxial line through a binding post to BNC connector adapter. This adapter does not terminate the coaxial line correctly, but increases the accuracy of the measurement considerably as shown in Figures V and VI. To reduce or eliminate reflections in the coaxial line, the proper impedance should terminate both or at least one end of the coaxial line. A BNC T-connector was used at the scope end of the coaxial line to connect the correct terminating impedance. The importance of retaining the coaxial line characteristic impedance is of the highest degree. The problems that may occur with improper termination may be predicted by transmission line theory. One of the problems is illustrated in Figures VIII and IX.

IV. CONCLUSION

In general, the coaxial resistor offers the best accuracy of current display for load line analysis. This is because of its frequency response and although the reactance of the coaxial resistor (as seen by the circuit) is not negligible, the shielding of the inside voltage sampling lead prevents radiation pickup. Resistance values can be quite low in this type of resistor. It is desirable to use as low a resistance as possible so the effect on circuit operation will be negligible.

TABLE OF ADDITIONAL TRANSISTOR LOAD LINES AND USES

NAME	**CIRCUIT**	**COMMENTS**
V_{CE} vs. V_{BE}		Indicates speed with which output follows input voltage. Also displays drive requirements.
I_C vs. V_{BE}		Indicates the degree of transistor cutoff. Also shows the possibility and degree of current concentration.
I_C vs. I_B		Beta at all points in the cycle is indicated. Since there is no common point for the two currents, base emitter drop should be taken into account, or the balanced ungrounded scope inputs should be used.
V_{CE} vs. I_B		Degree of saturation and storage time is here shown. Again there is no common point and the above corrections should be taken into account.

Note: In the above diagrams,

"C" indicates a common or ground point.
Black box indicates current measuring element.

The transformer current probe is quite useful for sine-wave frequencies of 1 kHz to 20 MHz. The Hall effect probe has the same characteristics as the current probe and the advantage of low-frequency response.

In many cases, a carbon resistor will provide adequate measurement. Carbon resistors are inexpensive, but low resistance values (less than 1 ohm) are difficult to obtain. This problem can be overcome to some extent by paralleling higher values.

Wire-wound resistors and straight wire resistors are not recommended.

Coaxial resistors may be constructed from the drawings in the appendix. The coaxial resistors built with steel shim stock must be limited to .15 watts dissipation. T & M Research Models SBNC-5-1 and SBNC-25-10 are good commercially available units for general use. The SBNC-5-1 has a resistance of 0.1 ohm and the SBNC-25-10 is 1.0 ohm. These resistors may be used up to 5 watts dissipation. The transformer current probe used for our experiments was a Tektronix P6019 with a 011-0078-00 termination. Also, the Hewlett-Packard 1110A probe and 1111A amplifier are available. The Tektronix P6042 dc current probe is an example of the Hall effect probe.

APPENDIX

The 2N2580 silicon transistor was used in the experiments shown in Figures I through VI. Figures I through V show the fall time of a square wave with the various types of resistors. The resistors are connected to the coaxial lead directly.

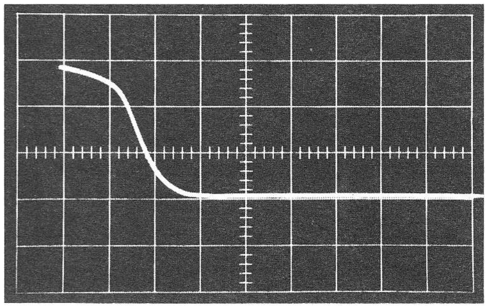


Figure I
Current through a 0.1 ohm coaxial resistor.
Vertical: 2 A/cm
Horizontal: 1μs/cm

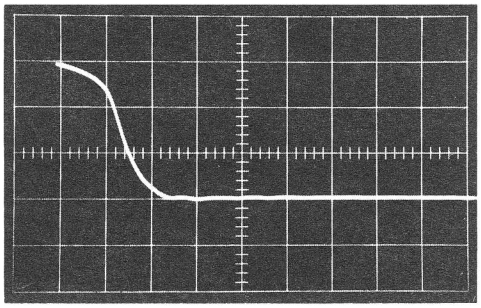


Figure II
Current through a 0.1 ohm carbon resistor.
Vertical: 2 A/cm
Horizontal: 1μs/cm

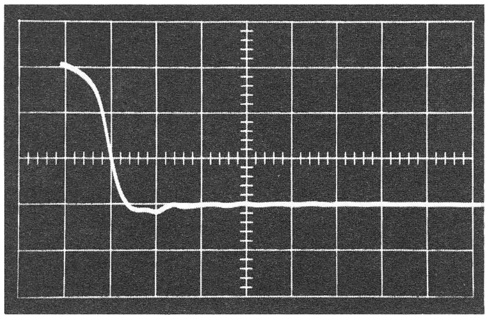


Figure III
Current through a 0.1 ohm wire-wound resistor.
Vertical: 2 A/cm
Horizontal: 1μs/cm

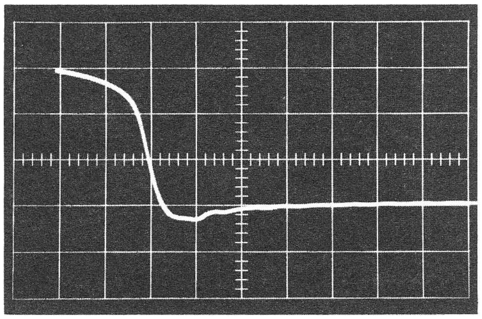


Figure IV
Current through a 0.1 ohm noninductive wire-wound resistor.
Vertical: 2 A/cm
Horizontal: 1μs/cm

Effects of resistors on fast fall and rise times with and without proper cable termination, figures VII, VIII and IX.

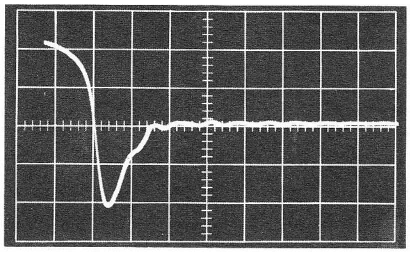


Figure V
Current through a 0.02 ohm one-inch straight manganin wire resistor, connected to the scope through a binding post to BNC connector adapter.
Vertical: 2.5 A/cm
Horizontal: 1μs/cm

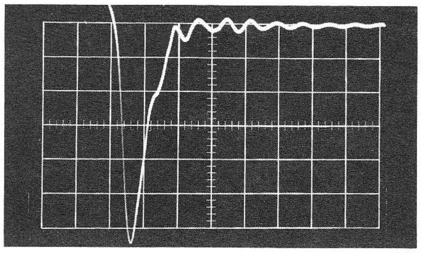


Figure VI
Current through a 0.02 ohm one-inch straight manganin wire resistor, connected to the scope with coaxial line and clip leads.
Vertical: 2.5 A/cm
Horizontal: 1μs/cm

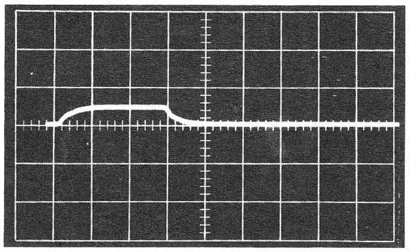


Figure VII
Current through a 0.1 ohm coaxial resistor with one end of coaxial line terminated in the characteristic impedance.
Vertical: 2 A/cm
Horizontal: 0.2μs/cm

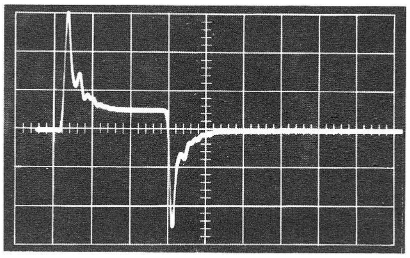


Figure VIII
Current through a 0.1 ohm carbon resistor with one end of the coaxial line terminated in the characteristic impedance.
Vertical: 2 A/cm
Horizontal: 0.2μs/cm

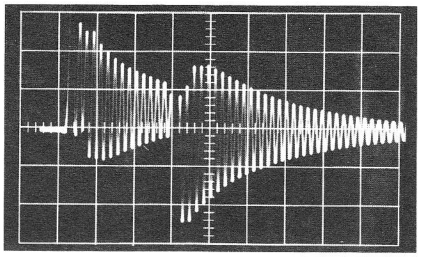


Figure IX
Current through a 0.1 ohm carbon resistor with improper cable termination.
Vertical: 2 A/cm
Horizontal: 0.2μs/cm

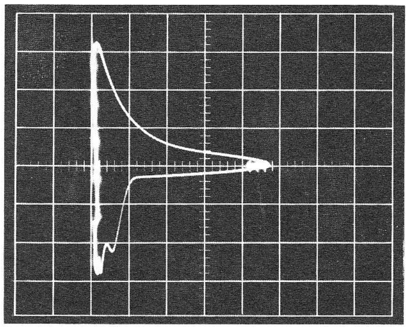


Figure X
Using a 0.1 coaxial resistor.

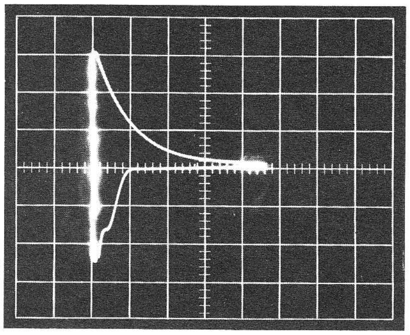


Figure XI
Using a P6019 current probe.

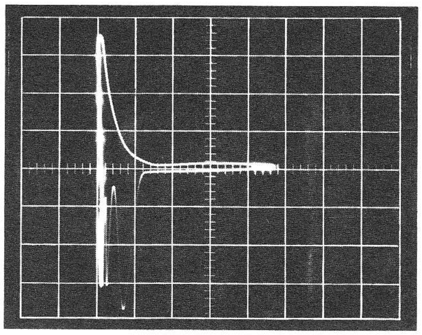


Figure XII
Using a 0.1 ohm carbon resistor.

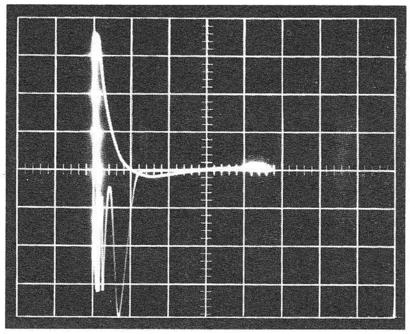


Figure XIII
Using a 0.1 ohm noninductive resistor.

Effect of resistor on load lines. The transistor used for Figure X through XV was a DTS-402. Proper cable termination was employed.
Vertical - Current: 1A/cm
Horizontal - Voltage: 10 V/cm
(for Figures X through XV)

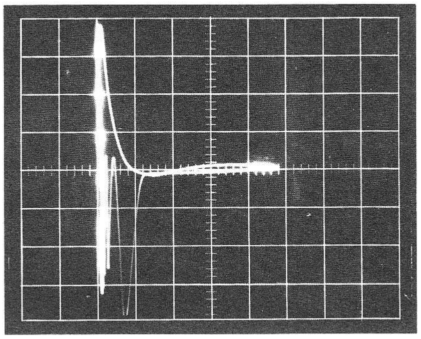


Figure XIV
Using a 0.1 ohm wire-wound resistor.

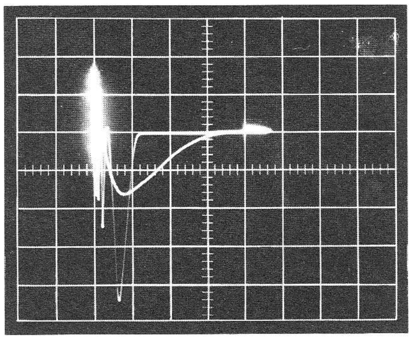


Figure XV
Using a 0.02 ohm one-inch straight manganin wire resistor.

SHEET METAL COAXIAL RESISTOR

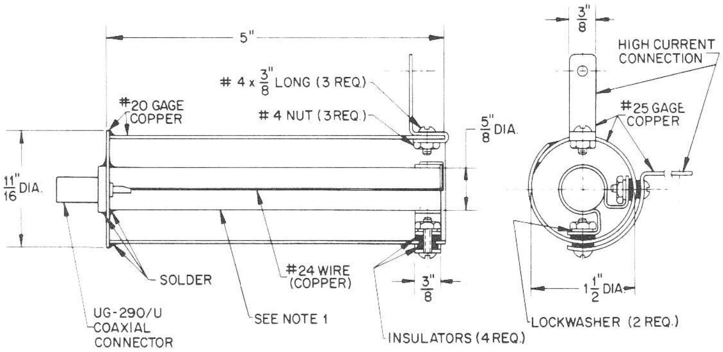


Figure XVI

Notes:

1. .001 steel shim stock - 2 turns - roll into tube 4-3/4 long. Adjust resistor to .005 ohm by flowing solder on shim stock. (Steel shim stock has a poor temperature coefficient. Manganin has a very good coefficient, but is hard to obtain in sheets.)

MACHINED COAXIAL RESISTOR

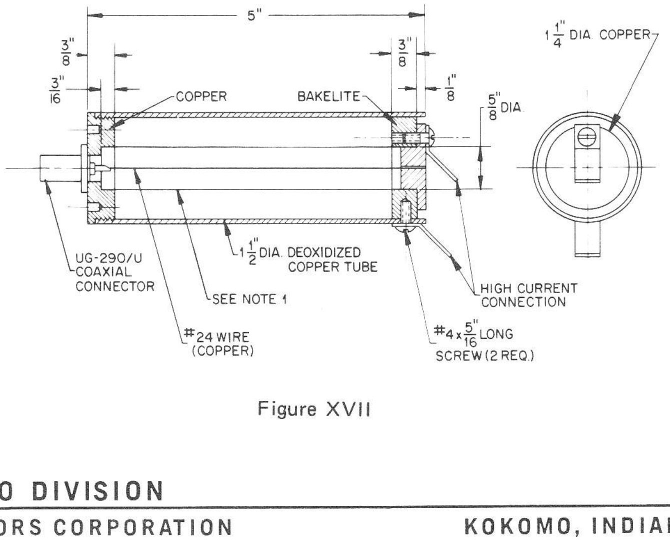


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Figure XVII